

A REVIEW OF THE SUPERSYMMETRY SEARCHES AT LEP

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The searches for supersymmetric particles by the four LEP experiments, ALEPH, DELPHI, L3, OPAL, have been made for many different theoretical models and phenomenological scenarios. Since no significant signs of a SUSY signal have been observed the results have been used to set exclusion limits and to constrain the supersymmetric parameter space. This talk will focus on combined SUSY searches, within the mSUGRA framework, from the four LEP experiments. The results are based mainly on the data recorded between the years 1996-2000, which corresponds to an integrated luminosity of 2.7 fb^{-1} and center-of-mass energies from 161 up to 208 GeV.

1 Introduction

The data recorded by the four LEP experiments, ALEPH, DELPHI, L3, OPAL, have been used to search for supersymmetry (SUSY). The results presented here will consist mainly of the combined results from the four LEP experiments produced by the LEP SUSY working group (LEPSUSYWG)¹. The data was recorded at $\sqrt{s} = 161 - 208 \text{ GeV}$ between the year 1996 and 2000 and corresponds to a total integrated luminosity of 2.7 fb^{-1} . Since no significant indications of SUSY were observed by any of the four experiments, cross section and exclusion limits were computed. All limits here are computed at 95% confidence level (CL) and should be regarded as preliminary. All cross section limits are shown at the highest center-of-mass energy recorded, $\sqrt{s} = 208 \text{ GeV}$.

Supersymmetry^{2,3,4} could be the solution to various unfavorable features of the standard model (SM), such as the hierarchy problem and it could provide a unification of the gauge couplings at the GUT scale. It could also be a possible solution to the dark matter problem and maybe be a step closer to a theory including gravity. The minimal supersymmetric extension of

the standard model (MSSM)^a introduces, however, over one hundred new parameters in its most general form. Many of these parameters can be constrained by existing experimental results, but the parameter space would even then be too large and arbitrary to encourage any specific SUSY searches. On the other hand, if the mechanism of the SUSY breaking^b was known, it would have large impacts on the phenomenology at lower energies. Hence a well motivated SUSY breaking mechanism imply a well motivated scenario to search for at the electroweak (EW) scale. Several SUSY breaking mechanisms have been assumed and searched for, where the so-called supergravity mediated SUSY breaking (SUGRA) is the most popular one. Another popular breaking mechanism is the so-called gauge mediated SUSY breaking (GMSB), where SUSY is broken by the SM gauge interactions. The phenomenology at lower energies normally differs significantly between different SUSY breaking mechanisms. In the SUGRA case a very heavy neutralino is normally the lightest SUSY particle (LSP) where as in GMSB it is normally a very light gravitino. Other assumptions like anomaly mediated SUSY breaking (AMSB), no-scale models etc. have also been searched for^{5,1}. In these models the LSP can be also other SUSY particles. However, even if a specific SUSY breaking mechanism increases the predictability the parameter space is still very large without any further assumptions.

For this reason some additional assumptions are normally made. The first assumption is that the sfermion and gaugino masses are unified at the GUT scale, where they can be represented by the sfermion and gaugino mass parameters m_0 and $m_{1/2}$ together with A_0 which determines the Yukawa couplings between the sfermions. The second assumption is whether R-parity^c is conserved or not. If R-parity is conserved it implies that the LSP is stable and the SUSY particles are produced in pairs. It is possible though that R-parity violating processes are allowed, without causing a very short proton lifetime, if the process originates from one of the three terms, LLE, LQD or UDD in the super potential.

One furthermore usually uses the knowledge about the EW symmetry breaking to decrease the number of parameters needed, so only the ratio of the vacuum expectation values from the two Higgs doublets $\tan\beta$ and the sign of the Higgs sector mixing parameter $sign(\mu)$ has to be added. Below are the parameter sets for the most common models used at LEP:

mSUGRA	$m_{1/2}, m_0, A_0, \tan\beta, sign(\mu)$
CMSSM	$m_{1/2}, m_0, A_t, m_A, \tan\beta, \mu$
GMSB	$F, M, N, \tan\beta, sign(\mu)$ ($\Lambda = F/M$)

All masses and couplings at the observable sector can therefore be determined from about five to six parameters without making drastic assumptions. In the constrained MSSM (CMSSM), which is more relaxed than the so-called minimal SUGRA (mSUGRA) scenario, one uses the two parameters A_t and m_A which corresponds to the trilinear coupling in the stop sector and the mass of the pseudoscalar Higgs. The parameters in the GMSB scenario are quite different due to the existence of an additional sector of messenger particles. Here the new parameters F , M and N corresponds to the intrinsic SUSY breaking scale, the messenger scale and a messenger index (the number of sets of messenger particles).

2 Experimental signatures and approach

At LEP one searches in general for a SUSY particle pair produced in the e^+e^- collisions. In the case of a produced slepton ($\tilde{\ell}$) pair, within the SUGRA framework, the slepton then normally

^aOnly consisting of the necessary super partners to the SM particles and a second Higgs doublet.

^bProviding the mass difference between the super partners and the corresponding SM particles.

^cRepresented by the multiplicative quantum number $R_p = (-1)^{3B+L+2S}$, where a SM particle obtains +1 and a SUSY particle -1.

decay into its corresponding lepton and a neutralino, giving rise to a leptonic event. A squark (\tilde{q}) pair would decay into a hadronic final state, but these searches and the corresponding results are described in detail in the presentation by A.C. Kraan and will hence not be further discussed here. In the case of a produced gaugino pair (chargino, $\tilde{\chi}^\pm$ or neutralino, $\tilde{\chi}^0$) the gaugino would normally decay into its corresponding gauge boson and a neutralino, where the gauge boson then decay into a leptonic or hadronic final state. The processes described above are the most common ones where as in some parts of the parameter space, the produced SUSY particles can also decay through cascade decays, e.g. $\tilde{\chi}^\pm \rightarrow W \tilde{\chi}_2^0 \rightarrow f f' \gamma \tilde{\chi}_1^0$, or through other SUSY particles, e.g. $\tilde{\chi}^\pm \rightarrow \ell \tilde{\nu} \rightarrow \ell \nu \tilde{\chi}_1^0$.

In the GMSB scenario, the topological signatures do not only differ due to the different kinematic properties of the LSP, but since the gravitino mass is allowed to be very light, the next to lightest SUSY particle (NLSP) can acquire a measurable life time. Hence it might not decay instantly at the interaction point, but might also decay inside or even outside the experiment. If then also R-parity violating decays are allowed, the LSP can decay into SM particles, increasing the number of tracks or jets, which increases the variety of signal topologies even further.

However, even if there are many different topologies where a SUSY signal could appear they all have the common characteristic missing energy from the escaping LSP (in the case where R-parity is conserved). Another very important quantity for the signal phenomenology is the mass difference $m_{NLSP} - m_{LSP} = \Delta m$. Hence a typical SUSY event at LEP would contain a SUSY particle pair, where the kinematic mass limit of the SUSY particles equals $\sqrt{s}/2$, which then decay into an event with missing energy characterized by the escaping LSP and with a visible energy constrained by the Δm value.

The results produced by the LEP SUSY working group are made in two steps. In order to be as model independent as possible, the number of observed events, the number of expected events from the SM and the corresponding signal efficiencies from the four LEP experiments are used to produce upper limits on the signal production cross section (σ_{95}) for the particular process searched for. At this stage the branching ratios into the specific decay channel are assumed to be 100%, so the cross section limits are mainly depending on the kinematic properties like m_{LSP} , Δm and \sqrt{s} . Since it is impossible to produce a totally model independent σ_{95} , one tries to only use the minimum set of required assumptions which are based on the most common signal behavior in order to make the limits as robust as possible. The second step is to interpret the σ_{95} and produce excluded SUSY particle masses and/or excluded regions in the SUSY parameter space and at this stage the more model dependent information, such as the branching ratios, are included.

3 SUGRA searches

The LEP searches within the SUGRA framework is the main part of the results being presented here and they are all based on the combined results from the LEPSUSYWG, where all the four LEP experiments, ALEPH, DELPHI, L3 and OPAL have contributed.

3.1 Sleptons

In the case of slepton pair production at LEP, the sleptons dominantly decay into their corresponding lepton and a $\tilde{\chi}^0$, giving rise to lepton final states with missing energy. In figure 1, the obtained cross section limits for \tilde{e} and $\tilde{\tau}$ pair production is shown in the selectron/stau-neutralino mass plane. The stau cross section limits is below 0.12 pb in almost the entire kinematically accessible region and the selectron cross section limit is in general below 0.05 pb. Cross section limits have also been computed for smuon pair production where the limit in the

smuon–neutralino mass plane is very similar to the selectron limits and below 0.05 pb in almost the entire plane.

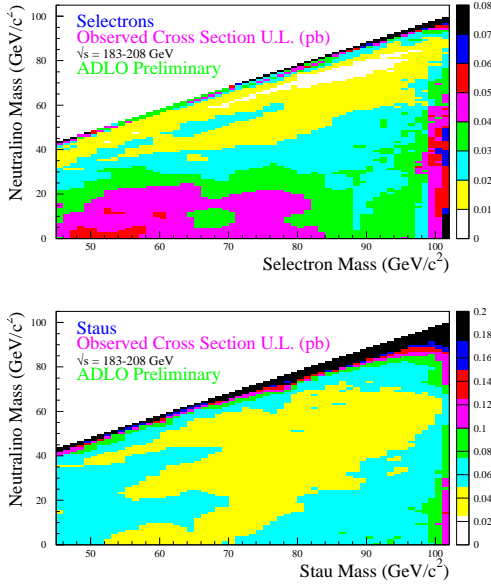


Figure 1: The selectron and stau production cross section limits at $\sqrt{s} = 208$ GeV.

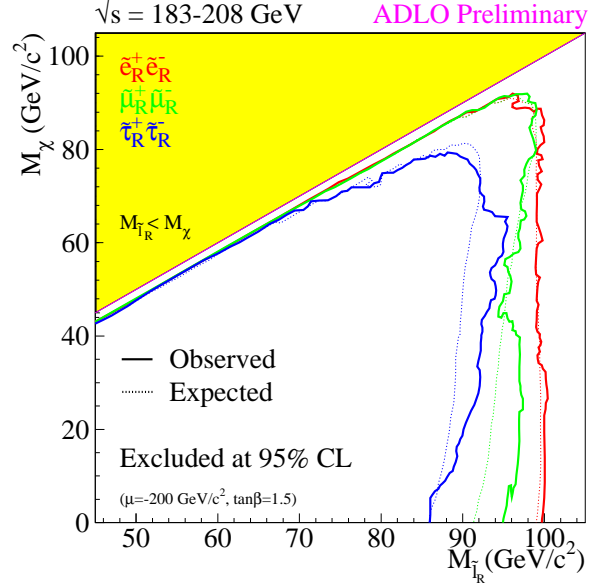


Figure 2: The slepton mass limits at $\mu = -200$ and $\tan \beta = 1.5$.

Mass limits for the different charged sleptons have been computed from the cross section limits and these are shown in figure 2. These limits have been obtained with $\mu = -200$ and $\tan \beta = 1.5$, which corresponds to a part of the parameter space where the slepton limits normally are able to provide constraints beyond the reach of the chargino and neutralino searches. The limits are furthermore obtained under the assumption of a negligible mixing of the sleptons and only the contribution of right handed sleptons is taken into account. This is conservative since $\tilde{\ell}_R$ has a lower cross section than the left handed partners. From figure 2 one can obtain the overall slepton mass limits $m_{\tilde{e}} > 99.6$ GeV, $m_{\tilde{\mu}} > 94.9$ GeV and $m_{\tilde{\tau}} > 85.9$ GeV, which are valid for Δm values above 15 GeV. Since a possible slepton mixing would be largest in the third family, a limit for the stau mass has also been computed in the scenario with a stau mixing that minimize the production cross section for the lightest stau and this limit corresponds to $m_{\tilde{\tau}} > 85.0$ GeV.

3.2 Charginos

The first combined chargino results concerns a possible chargino production at large values of m_0 and for Δm values above 3 GeV. Due to the high m_0 value the chargino would decay dominantly into a W and a $\tilde{\chi}^0$. For this reason, the search is performed using three different signal topologies characterized by: two charged leptons, one charged lepton plus two jets or four jets. Figure 3 shows the chargino cross section limit in the chargino–neutralino mass plane and the cross section limit is below 0.8 pb in most of the region kinematically allowed. The chargino pair cross section is generally very high in most of the accessible parameter space, but since the t-channel sneutrino exchange diagrams causes destructive interference, there are parts of the parameter space at low m_0 values where the chargino search is insensitive. Figure 4 shows the chargino mass limit as a function of the sneutrino mass in a part of the parameter space where the chargino couples strongly to the sneutrino ($\mu = -200$ and $\tan \beta = 2$) and from this plot one obtains a mass limit of $m_{\tilde{\chi}^\pm} > 103.5$ GeV for $m_{\tilde{\nu}} > 300$ GeV. In figure 4 it can also be seen

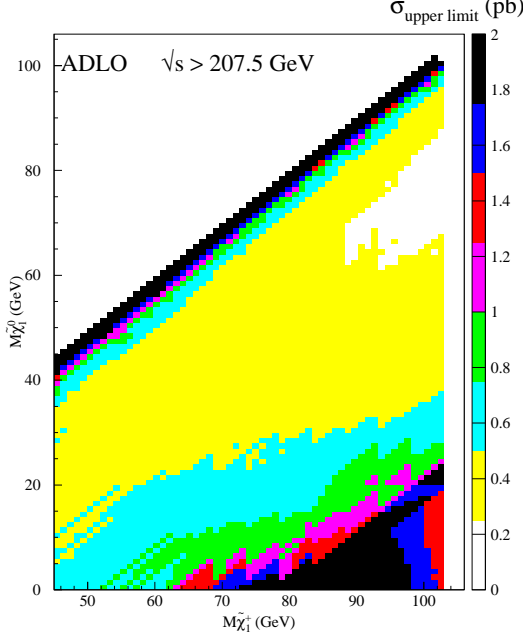


Figure 3: The chargino pair production cross section limits at $\sqrt{s} = 208$ GeV.

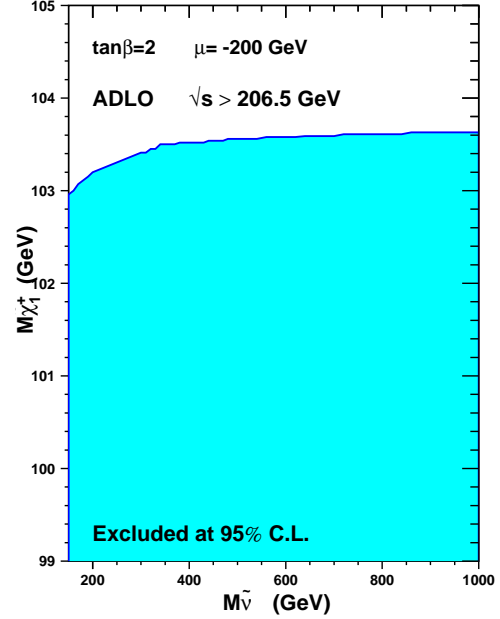


Figure 4: The chargino mass limit as a function of the sneutrino mass at $\mu = -200$ and $\tan\beta = 2$.

that the sensitivity of the large m_0 search decrease rapidly at lower Δm values and since these values are allowed, in models like mSUGRA and CMSSM, also the searches investigating this region have been combined. For low Δm values several different analysis have been used due to the fast change of the topological signature of the signal. For Δm values above 3 GeV the large m_0 search has been used. For values between about 200 MeV upto 3 GeV, searches based on soft events with initial state radiation (ISR) have been used. The ISR photon in these events is used to increase the suppression of soft two photon event background. At Δm values below 200 MeV, the chargino gets a measurable lifetime and can decay inside or outside the experiment. So in this case the searches based on events with large impact parameters or tracks with kinks are used together with the search for heavy stable particles.

The results have then been used to compute chargino mass limits in two different scenarios. The first scenario is where the chargino is higgsino dominated which corresponds to where low Δm values occur in models like mSUGRA and CMSSM. In this case the negative interference from the sneutrino diagrams are negligible since the sneutrino couples to the gaugino part. The second scenario is for a gaugino dominated chargino (where the gaugino mass unification assumption is relaxed) with a high sneutrino mass. A chargino mass limit has been computed as a function of the Δm value for both the higgsino and gaugino case. The mass limit changes in a very similar manner in the two scenarios and in both cases the overall limit is found at a Δm value of around 200 MeV and corresponds to $m_{\tilde{\chi}^\pm} > 92.4$ GeV for the higgsino scenario and $m_{\tilde{\chi}^\pm} > 91.9$ GeV for the gaugino scenario.

3.3 LSP

The results from the slepton, chargino, neutralino and SM Higgs searches have been combined to determine an overall LSP mass limit. The combined LSP limits have been computed within both the CMSSM and the mSUGRA framework using different approaches. Figure 5 shows the LSP limit as a function of the $\tan\beta$ value for the CMSSM scenario. The limit is made by a scan of $\tan\beta$, m_0 , $m_{1/2}$ under the assumption that the stau has a negligible mixing. For each

point in the scan the cross section limits from the searches presented above are used to exclude the point by comparing the calculated values of the cross section and branching ratio with the limit of the relevant processes. The parameter assumptions regarding the Higgs sector are made conservatively¹ and to obtain the lightest Higgs mass the HZHA generator has been used which includes the most recent radiative corrections. The minimum LSP limit have been set by the large m_0 searches for $\tan\beta < 4$, where the limit is determined by the SM Higgs (hZ) search for $\tan\beta < 2.5$ and by the chargino search for $2.5 < \tan\beta < 4$. For $\tan\beta > 4$ the limit is set at small m_0 , where it is obtained by the SM Higgs search for $\tan\beta < 4.2$ and for $\tan\beta > 4.2$ by the slepton search. Figure 5 shows that the overall LSP limit in the CMSSM scenario corresponds to $m_{LSP} > 45$ GeV, where the uncertainty, due to tree level calculations of the gaugino masses and unification, is estimated to be of the order $\mathcal{O}(1 \text{ GeV})$.

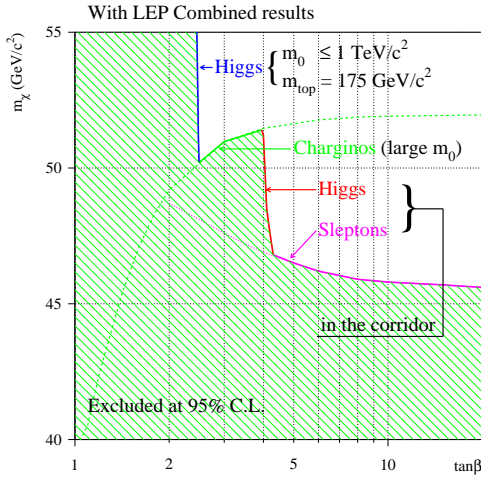


Figure 5: The LSP limit as a function of $\tan\beta$ within the CMSSM.

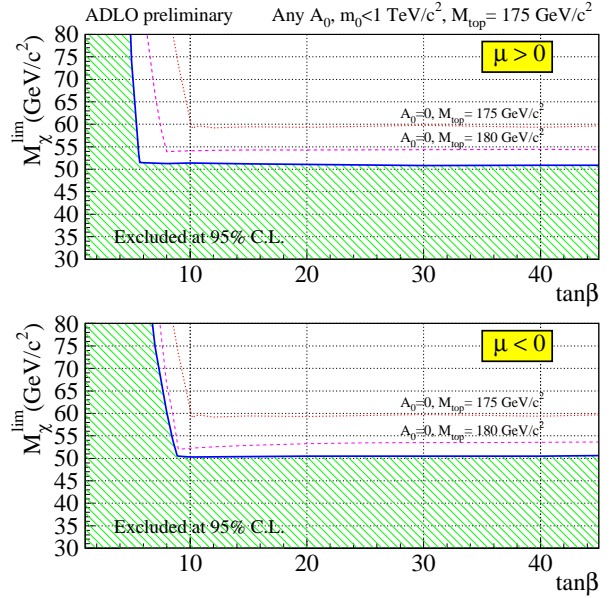


Figure 6: The LSP limit as a function of $\tan\beta$ within the mSUGRA for positive and negative $\text{sign}(\mu)$.

Figure 6 shows the LSP limit as a function of $\tan\beta$ for both positive and negative signs of μ in the mSUGRA scenario. In this case a scan of m_0 , $m_{1/2}$, and A_0 have been performed for each point in the $\tan\beta$, $\text{sign}(\mu)$ plane. The scan has then been constrained using the results from the Z width measurement by the LEP EW working group, the Higgs (hZ) search limits (adapted for both the SUSY h and H) and the heavy stable stau search. The points surviving these constraints were then further constrained by the direct electron search, the stau search and the chargino search. The solid line corresponds to the obtained limit for any value of A_0 and the dotted and dashed lines corresponds to the limits obtained with $A_0 = 0$ for the two different top quark masses, $m_{top} = 175 \text{ GeV}$ and $m_{top} = 180 \text{ GeV}$ respectively. The LSP limits shown in figure 6 have been obtained at large m_0 and were set by the Higgs search at small $\tan\beta$ (being strongest for $\mu < 0$) and by the chargino search at large $\tan\beta$. The obtained overall mSUGRA LSP mass limit for positive μ was $m_{LSP} > 50.8 \text{ GeV}$ and $m_{LSP} > 50.3 \text{ GeV}$ for negative values of μ . For the mSUGRA LSP limit also radiative corrections to the chargino and neutralino masses have been included.

3.4 R_p violation

Searches for R-parity violating processes have also been made where the results from the search of processes originating from the lepton number violating LLE term in the SUSY potential have

been combined. These results are for the so-called indirect scenario, which corresponds to SUSY particle pair production where the SUSY particles decay like R-parity conserving processes but with the difference that the LSP then decay into SM particles. The searches have been made for a neutralino mass above 10 GeV to ensure an instant decay at the interaction point. In this scenario, the results from the slepton searches have been combined and a cross section limit below 0.02 pb has been obtained in almost the entire accessible neutralino–slepton mass region in the selectron, the smuon and the stau search. The results have then been interpreted as mass limits, where one obtains the slepton mass limits, $m_{\tilde{e}} > 96.6$ GeV, $m_{\tilde{\mu}} > 96.9$ GeV, $m_{\tilde{\tau}} > 95.9$ GeV, for $\Delta m > 3$ GeV, $\mu = -200$ and $\tan\beta = 1.5$. In order to be conservative, only the right handed charged slepton contribution have been taken into account, since they always have a lower cross section than the left handed SUSY partners. The search for sneutrinos have also been combined under the same assumptions and the obtained mass limits are $m_{\tilde{\nu}_e} > 98.9$ GeV and $m_{\tilde{\nu}_\mu} > 84.5$ GeV.

4 GMSB searches

In the GMSB scenario, the NLSP is either the neutralino or one of the charged sleptons. In the case of a neutralino NLSP, the neutralino will decay dominantly into a photon and an escaping gravitino. For an instantly decaying $\tilde{\chi}^0$, the main process to search for is a neutralino pair which give rise to acoplanar two photon final states. The results from this search have been combined and the cross section limit for neutralino pair production is $\sigma_{95}(\tilde{\chi}^0\tilde{\chi}^0) < 0.025$ pb for $m_{\tilde{\chi}^0} < 102$ GeV.

In the slepton NLSP scenario, the slepton would decay into its corresponding lepton and a gravitino. Results both from searches of instantly decaying sleptons and from searches for slepton with a measurable life time have been combined. This has made it possible to obtain slepton mass limits within the GMSB scenario which are valid for any life time and which are, $m_{\tilde{e}} > 65.8$ GeV, $m_{\tilde{\mu}} > 96.3$ GeV and $m_{\tilde{\tau}} > 86.9$ GeV. Under the assumption of an instantly decaying NLSP the neutralino and slepton results have been used together with the LEP1 results to make exclusions in the GMSB parameter space. Figure 7 shows the excluded region in the Λ – $\tan\beta$ plane, where the assumptions $N = 2$, medium M and $\mu > 0$ have been used and one can see that the LEP2 results exclude a very significant part of the kinematically accessible region.

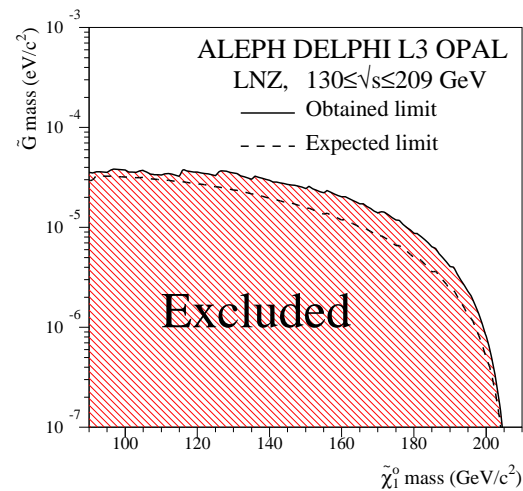
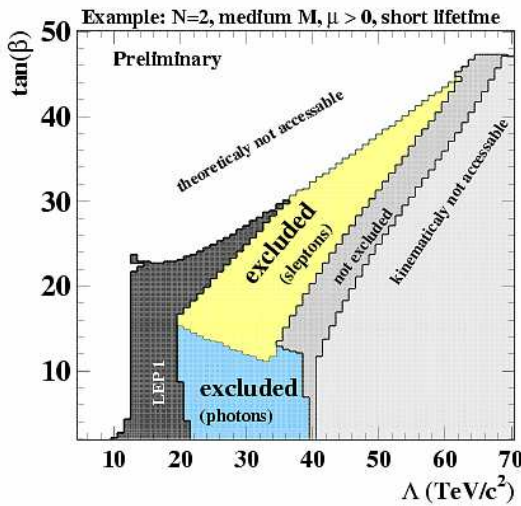


Figure 7: The excluded region in the GMSB Λ – $\tan\beta$ plane. Figure 8: The excluded region in the neutralino–gravitino mass plane according to the LN2 model.

5 Other searches

Searches for more unconventional scenarios have also been performed. The results from the single photon analysis by the four LEP experiments have for example been used to search for SUSY within the so-called LNZ (J.L. Lopez, D.V. Nanopoulos, A. Zichichi) model. This is a string motivated no-scale model where all parameters can be derived from one parameter, $m_{\tilde{\chi}^0}$, except the gravitino mass which is favored to be less than $\mathcal{O}(1 \text{ KeV})$. Figure 8 shows the excluded region in the neutralino–gravitino mass plane according to the LNZ model obtained from the combined results from the four LEP experiments.

Also searches for SUSY within the so-called anomaly mediated SUSY breaking model have been made. In this model the SUSY breaking originates only from anomaly terms in the supergravity Lagrangian. This implies that the minimal AMSB can be described by only the four parameters, $m_{3/2}$, $\tan\beta$, m_0 and $\text{sign}(\mu)$. The LSP in AMSB can be either the neutralino, the sneutrino or the stau. The DELPHI collaboration has made searches for AMSB within many different topologies, using also the results from the Higgs search, and then performed a scan over the AMSB parameter space. From this scan overall mass limits were obtained for the neutralino and the sneutrino of $m_{\tilde{\chi}^0} > 68 \text{ GeV}$ and $m_{\tilde{\nu}} > 98 \text{ GeV}$.

6 Conclusions

During the period of LEP2 no significant indications of SUSY were observed in any of the LEP experiments and the collected data sample of $\mathcal{L} = 2.7 \text{ fb}^{-1}$ and with \sqrt{s} up to 208 GeV, has been used to constrain the accessible SUSY parameter space under the assumption of various SUSY breaking mechanisms and phenomenological scenarios. Many of the searches made by the individual experiments have now been combined, providing the tightest possible bounds on various supersymmetric models. Further results and details can be found at the LEP SUSY working group homepage, <http://lepsusy.web.cern.ch/lepsusy/Welcome.html>.

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